REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. Agency Use Only *(Leave Blank)*.

2. REPORT DATE
December 1998

3. REPORT TYPE AND DATES COVERED
Proceedings

4. TITLE AND SUBTITLE

Frontal Instabilities in a Buoyant Plume

5. FUNDING NUMBERS
Job Number
Program Element 0602435N
Project No.
Accession No.

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION AND ADDRESS
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/PP/7331--99-0015

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Proceedings of the First Southern Symposium on Computing, 4-5 December 1998, The University of Southern Mississippi, Hattiesburg, MS
*Sverdrup Technologies Inc., Stennis Space Center, MS 39529-5004

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT

Many phenomena in the coastal ocean produce surface signatures that appear in remotely sensed images. We are interested in understanding the dynamics that control these phenomena, particularly those seen in Synthetic Aperture RADAR (SAR) images. Some of the signatures in SAR images are associated with convergence fronts produced by buoyant plumes. Fresh water discharges from rivers and bays into the saltier shelf water can form such plumes. The plumes and the associated fronts can extend for hundreds to thousands of meters and have widths of meters to tens of meters. The plumes can propagate tens to a hundred of kilometers from their source.

We used three models to simulate buoyant jets: a 2-D nonhydrostatic channel model, a 3-D nonhydrostatic Large Eddy Simulation (LES) model and a 3-D hydrostatic model. The hydrostatic model is the Navy Coastal Ocean Model (NCOM) which is a component of the Coupled Ocean Atmosphere Prediction System (COAMPS). The LES model separates the flow by physical scales rather into mean and turbulent components. The nonhydrostatic models simulated the "Lock Exchange" problem using idealized geometries at relatively small scales. The hydrostatic models simulates the Chesapeake Bay outflow plume using realistic topography and geometry.

14. SUBJECT TERMS
buoyant plumes, SAR, AVHRR, Chesapeake Bay, NCOM simulations, nonhydrostatic, COAMPS, and LES (Large Eddy Simulation)

15. NUMBER OF PAGES
7

16. Price Code

17. Security Classification of Report.	18. Security Classification of This Page.	19. Security Classification of Abstract	20. Limitation of Abstract
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)

PROCEEDINGS OF THE FIRST SOUTHERN SYMPOSIUM ON COMPUTING

December 4-5, 1998 · The University of Southern Mississippi · Hattiesburg, Mississippi

edited by

Marcin Paprzycki and Joseph Kolibal

Published by
School of Mathematical Sciences
The University of Southern Mississippi
Hattiesburg, MS 39406
April, 2000
ISBN: 0-9677774-0-2

proceedings have finally been published
you can list the paper as in print

7/5/00

Proceedings of the First Southern Symposium on Computing
The University of Southern Mississippi, December 4-5, 1998

FRONTAL INSTABILITIES IN A BUOYANT PLUME

PATRICK C. GALLACHER*, MICHAEL SCHAFERKOTTER†, AND PAUL J. MARTIN‡

Abstract. Many phenomena in the coastal ocean produce surface signatures that appear in remotely sensed images. We are interested in understanding the dynamics that control these phenomena, particularly those seen in Synthetic Aperture RADAR (SAR) images. Some of the signatures in SAR images are associated with convergence fronts produced by buoyant plumes. Fresh water discharges from rivers and bays into the saltier shelf water can form such plumes. The plumes and the associated fronts can extend for hundreds to thousands of meters and have widths of meters to tens of meters. The plumes can propagate tens to a hundred of kilometers from their source.

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The hydrostatic model is forced with climatological river outflow in the Chesapeake and Delaware bays, 8 tidal components and a wind field that rotates counterclockwise with a 10 day period. This later crudely simulates the passage of weather systems. The hydrostatic model can be configured with several nested grids. In the simulation discussed here we use three grids: an outer grid with a horizontal resolution of 2 km, the first nested grid with a horizontal resolution of 666 m and the second nested grid with a horizontal resolution of 222 m.

In the 2-D nonhydrostatic channel simulations plumes develop and propagate at roughly the correct speed. The shape and location of the turbulent rotor, the mixing region and the laminar flow region agree qualitatively with laboratory measurements. In the 3-D nonhydrostatic simulations the plume also develops and propagates at roughly the correct speed. The rotary current develops around the head with strong downwelling in front of the head and upwelling behind the head. The lighter water overtakes the top leading edge of the plume front and contributes to the downwelled mass. Waves begin to appear behind the head along the boundary between the warm and cold water. No transverse or three dimensional structures have started up to this point.

The NCOM simulations agree qualitatively with observations of the Chesapeake Bay outflow plume. The plume is strongly forced by the tides and is modulated by the winds. Northerly winds push the plume south and compress it against the coast. Southerly winds widen the plume and the upwelling induced on the onshore side of the plume forces the plume off shore.

1. Introduction. Numerous phenomena in the ocean produce a variety of surface signatures that can be seen in remotely sensed images. These signatures exist at many different spatial scales and persist for various lengths of time. Signatures in the sea surface temperature (SST) field can be seen in AVHRR images, sea surface salinity (SSS) field patterns can be detected using the salinity mapper, and variations in sea surface roughness can be seen in synthetic aperture radar (SAR) images.

We are interested in understanding the dynamics that produce some of these surface signatures, in particular those seen in SAR images. These patterns can be meters to tens of meters wide and hundreds to thousands of meters long. One phenomena that frequently produces banded structures seen in SAR images are ocean fronts, particularly those associated with convergence.

Rivers, large and small, discharge fresh water onto the continental shelf where it eventually mixes with more saline shelf/slope water. The river discharge varies seasonally and synoptically and it is modulated by the tides. The combined effects of tides, topography, and wind create a series of fronts associated the fresh water discharge. In cases of large discharge, these fronts can persist for significant periods of time and form coastal buoyant plumes that propagate along the coast for considerable distances, sometimes hundreds of kilometers.

As part of the Physics of Coastal Remote Sensing (CoRS) Advanced Research Initiative (ARI) we have been studying the Chesapeake Bay outflow plume in some detail. It is a good example of a large discharge case. The plume is clearly visible in measurements of sea surface temperature and

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sea surface salinity and it is clearly seen by the naked eye in the sea surface roughness. The front is still quite visible at Duck, North Carolina which is roughly 70 kilometers south of the mouth of Chesapeake Bay.

The CoRS ARI is a five year program at the Naval Research Laboratory funded through the Office of Naval Research designed to understand the dynamics responsible for the surface signatures seen in remotely sensed images of the coastal ocean. This project seeks to understand how to use data fusion to enable multiple remote sensing and in-situ ocean data inputs to be used synergistically to specify coastal ocean features. To this end four field experiments have been conducted and one more is planned. Also several new remote sensing instruments have been developed as part of this project. The project also seeks to understand how to combine models of small-scale dynamical features with coarser resolution, broad shelf-scale models and how to merge the corresponding multi-scale data into these models as initial conditions. For this purpose several models are being used, develop, and created.

In this paper we will discuss the results and numerical methods of three of these models. The first is a two dimensional channel model that can easily examine the effects of using the hydrostatic approximation. The second is a Large Eddy Simulation (LES) model designed to study small scale turbulent ocean flows. The LES model is nonhydrostatic. The third is the Navy Coastal Ocean Model (NCOM) which is being developed as part of the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS). The NCOM is hydrostatic.

In section two we will write down the nonhydrostatic Navier-Stokes equations so we distinguish the effects of the hydrostatic approximation. Then the models and their results will be discussed in the next three sections and conclusions will be drawn in section six.

2. Basic Equations. The mathematical equations we employ to describe the motions of water on the surface of the earth are the Navier-Stokes equations with the Boussinesq and incompressible assumptions (see [1] for a derivation and discussion of these equations). The Boussinesq and incompressible assumptions together eliminate any dependence of the dynamics on the density, except for buoyant forcing in the vertical direction and pressure gradient forces. In a cartesian coordinate system, with the x-y plane tangent to the surface of the ocean and the axes oriented such that the positive x axis points eastward, the positive y axis points northward, and the positive z axis points upward, the Navier-Stokes equations can be written as:

$$\frac{Du}{Dt} - \frac{uv\,tan(\phi)}{a} + \frac{uw}{a} + \frac{1}{\rho}\frac{\partial p}{\partial x} - f_n v + f_t w = F_x \tag{2.1}$$

$$\frac{Dv}{Dt} - \frac{u^2\,tan(\phi)}{a} + \frac{vw}{a} + \frac{1}{\rho}\frac{\partial p}{\partial y} - f_n u = F_y \tag{2.2}$$

$$\frac{Dw}{Dt} - \frac{u^2 v^2}{a} + \frac{1}{\rho}\frac{\partial p}{\partial z} + g' - f_t u = F_z \tag{2.3}$$

Since the fluid is incompressible the prognostic equation for density reduces to the continuity equation $\nabla \cdot \mathbf{V} = 0$ and the equation of state which relates the density to the thermodynamic variables is $\rho = \rho(s, T, p)$ where the salinity, s, and the temperature, T, have prognostic equations of the form:

$$\frac{Ds}{Dt} = F_s\,,$$

$$\frac{DT}{Dt} = F_T\,.$$

In the above equations

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$$

is the substantial, or total, derivative, and u, v and w are the velocities in the eastward, northward and upward directions. The buoyancy forcing is written in terms of a "reduced" gravity,

$$g' = \frac{g(\rho - \rho_0)}{\rho_0} \tag{2.4}$$

F_a represents the forcing and diffusion terms for the variable a. The components of the Coriolis force tangential to and normal to the surface of the ocean are $f_t = 2\Omega sin\theta$ and $f_n = 2\Omega cos\theta$ respectively, where Ω is the rotation rate of the earth and θ is the latitude. The tangential component is usually neglected in the hydrostatic limit but is required in the nonhydrostatic limit. The second term in the w equation and the second and third terms in the u and v equations are related to the curvature of the earth. They are also neglected in the hydrostatic limit but are required in the nonhydrostatic case for conservation of momentum (see [2] for details). The tangential Coriolis terms and the curvature terms are most significant only at large scales. The nonhydrostatic simulations discussed here are at small scales so we neglect those terms. In the hydrostatic approximation, all the terms in the w equation are neglected except the pressure gradient and the buoyant forcing.

3. 2-D nonhydrostatic channel simulation. The model is a 2-D channel model with a free surface with no heat flux through the surface. The boundary conditions at the bottom of the channel are no slip for the horizontal velocity components and zero for the normal component. The temperature boundary condition is no flux. There are open boundaries at the ends. The model is nonhydrostatic. It uses finite difference methods in space and time. The eddy diffusivity is split into a horizontal and vertical component. Each component has a constant background value and a part that varies to maintain horizontal and vertical grid cell Reynolds numbers of 10. The horizontal and vertical grid cell Reynolds numbers are $Re_h = \nu\frac{U}{\Delta x}$ and $Re_v = \nu\frac{W}{\Delta z}$, respectively.

For the nonhydrostatic simulation discussed in this article, the channel is 20 kilometers long and is spanned by 1000 grid points for a resolution of $dx = 20$ m. The channel is 200 m deep in the deep half and 100 m deep in the shallow half with a resolution of 4 m. The time step is 3 seconds and the simulation is carried out for 20 minutes. The background diffusivity in the horizontal direction is $K_h = 0.2\text{m}^2\text{s}^{-1}$ and in the vertical direction, $K_v = 0.01\text{m}^2\text{s}^{-1}$. The diffusivities are adjusted to keep the maximum grid cell Reynolds number at 10. The initial condition is a sharp salinity gradient of 6.7 psu separating two otherwise homogeneous water masses on each half of the channel.

The numerical experiment simulates the "lock exchange" problem in which two water masses with different densities are separated by a lock. The lock is removed and two plumes form and spread in opposite directions [6]. The low density plume propagates over the top of the denser fluid and a high density plume propagates under the lighter fluid. The mean velocity of the plumes can be approximated from hydraulic theory, using Bernoulli's equation combined with the continuity equation and the fact that the total pressure force plus the momentum flux per unit span is constant. However, if the plume is less than half the depth of the channel mixing must occur to dissipate energy at the nose of the front. In that case, the behavior is significantly more complicated and either a parameterization of the turbulent mixing is required or, if the details of the flow are important, a fully nonhydrostatic model is required to simulate the flow.

In these numerical simulations the initial salinity distribution is a hyperbolic tangent function in the x direction (Figure 1) and is independent of y and z. The fluid is initially at rest and the front is initially on the shallow side just to the left of the step increase in depth between the shallow and deep water at the center of the channel. The average propagation speed of the plumes are approximately the internal wave speed, which is roughly the same on either side of the depth break (Figure 2). The plumes develop circulation patterns that are characteristic of buoyantly driven plumes. There is head region consists of a turbulent rotor with a recirculation of fluid around it consisting of a downwelling of fluid in front of the plume and an upwelling behind the turbulent rotor. The mixing is greatest just behind the rotor and the flow becomes more laminar with increasing distance behind the head region. The thickness of the head region is greater on the deeper side and the flow behind the head is more laminar than on the shallow side. The results agree qualitatively with laboratory measurements [5].

4. LES Model. The standard equations used in oceanography are the "Reynolds Averaged" Navier-Stokes equations. Reynolds Averaging separates the flow into its mean and turbulent components. The turbulent component is then parameterized by some mixing model. The unique aspect of the LES model is that it attempts to separate the flow based on physical scales rather than by Reynolds averaging. In this way all the flow features that can be resolved on the numerical grid are simulated and only the unresolved, or subgrid scale, aspects of the flow are parameterized.

The separation is accomplished by spatially filtering in the wavenumber domain with a low-pass filter. The need to filter in wavenumber space makes spectral techniques particularly appealing. Thus the model uses Fourier transforms in the horizontal to allow the derivatives to be calculated in wavenumber space. This also greatly simplifies solving the Poisson equation for the pressure. The vertical derivatives are in finite difference form to allow mixed boundary conditions in the vertical. The time stepping is Adams-Bashforth.

The energy in the subgrid scale is calculated using a modified energy budget and is used to specify a dynamically varying eddy viscosity and diffusivity. The details of the filtering and the subgrid scale energy equation are discussed in [4] and [3]. The model is nonhydrostatic. The boundary conditions are periodic in the horizontal (x and y). The top boundary conditions specify the momentum and heat flux. The bottom boundary conditions are either a rigid wall, no slip and no heat flux, free slip, zero fluxes at the bottom, or a radiation boundary condition. The later implies no bottom in the vicinity of the bottom of the model domain.

The initial conditions are a hyperbolic temperature (rather than salinity) distribution in the x direction with cosine tails to provide the periodic horizontal boundary conditions. (Figure 3). The temperature difference across the front is 10° C. This is equivalent to a salinity difference of 2.5 psu. There is no initial temperature variation in the y or z directions. The fluid is initially at rest as in the previous 2-D simulation. The domain is 450 m in the x direction, 75 m in the y direction and 30 m deep. There is no rotation in this simulation.

The mean velocities after 100 seconds of integration are $U = 85$ ms^{-1}, $V = 0.01$ cm-s^{-1} and $W = 30$ cm-s^{-1}. The surface plume forms and moves to the left (Figure 4) over the cold water. Water in the plume overrides the front at the top and downwells. Behind the head of the plume the water upwells, where the upward kink in the 20° C isotherm is located. This circulation forms the turbulent rotor. There is some evidence of waves on the 20° C isotherm near the back of the rotor. However, there hasn't been sufficient time for turbulent mixing to develop and no 3-D features or transverse flows have started yet. The plume has already begun to take on the classic buoyant plume shape as also seen in the 2-D simulations and in laboratory measurements [5].

5. NCOM. The NCOM is based on Princeton Ocean Model (POM) code. It utilizes a combined sigma-z vertical coordinate. In the sigma coordinate system the total depth is divided into n levels. The i^{th} level has a thickness of

$$\frac{dz(i)}{D(x,y)} \tag{5.1}$$

where $D(x,y)$ is the total depth of the sigma coordinate portion of the vertical domain. Thus the thickness of each level can vary horizontally. In the z portion of the vertical domain the thicknesses of the levels are fixed. The free surface in the model is treated implicitly. The horizontal grid can be curvilinear but a rectangular domain is used for this experiment. An arbitrary number of nests are built in, for this experiment three levels of grids are used. An outer grid and two nested grids. The time advancement is leapfrog with an Asselin temporal filter to suppress timesplitting.

NCOM uses the primitive equations. The physics are incompressible, hydrostatic, and Boussinesq. For this experiment a grid cell Reynolds number horizontal mixing scheme is used and the vertical mixing uses a Mellor-Yamada level 2 scheme. The bottom drag is quadratic. There are source terms for river inflow.

In the simulation discussed here we use three grids: an outer grid with a horizontal resolution of 2 km, the first nested grid with a horizontal resolution of 666 m and the second nested grid with a horizontal resolution of 222 m. The coarse resolution grid covers the region from north of Delaware

Bay to south of Duck North Carolina including all of Delaware and Chesapeake bays and east to the shelf break. The finest resolution grid covers the southern third of the mouth of the Chesapeake Bay to south of Rudee Inlet (Figure 5).

For this simulation NCOM is forced with climatological river flows into the Delaware and Chesapeake Bays, 8 tidal constituents and a wind field that rotates counterclockwise with a 10 day period. This later crudely simulates the passage of weather systems.

In the image on the left side of Figure 5, the yellow and green colors represent fresh water flowing out of the mouth of the Chesapeake Bay into the saltier, orange coastal waters. The fresh water is supplied by rivers flowing into the Chesapeake Bay. The plume is strongly forced by the tides and is strongly modulated by winds. The plume flows to the south after exiting the mouth of the bay.

The tides force the plume into a pulsed output with the maximum occurring on the ebb tide. Usually several fronts are visible. Frequently these are residual fronts left from the previous tidal excursion when the flood tide pushed the plume back toward or into the mouth of the bay.

The image (Figure 5) shows a typical plume during the ebb tide with roughly northwesterly winds. The winds from an easterly to northerly quadrant push the plume into the coast and further south. When the winds are from the westerly to southerly quadrant the plume widens, upwelling occurs at the onshore side of the plume and the plume is pushed offshore. The size and shape of the plume agrees with AVHRR and salinity mapper images.

In the image on the right the colors represent SSS gradient enhanced to show regions with the gradients of 1-2 psu/km. The kinks, cusps and contortions of the front are the results of dynamic instabilities, turbulent mixing and gravity wave generation and propagation. We are using the 2-D and 3-D models discussed above to understand the nature of these instabilities. The resulting streaks of high SSS gradient are qualitatively similar to SAR images in shape, extent and movement. The SAR images reveal locations of convergence fronts.

6. Conclusions. In the 2-D nonhydrostatic channel simulations plumes develop and propagate at roughly the correct speed. The shape and location of the turbulent rotor, the mixing region and the laminar flow region agree qualitatively with laboratory measurements.

In the 3-D nonhydrostatic simulations the plume also develops and propagates at roughly the correct speed. The rotary current develops around the head with strong downwelling in front of the head and upwelling behind the head. The lighter water overtakes the top leading edge of the plume front and contributes to the downwelled mass. Waves begin to appear behind the head along the boundary between the warm and cold water. No transverse or three dimensional structures have started up to this point.

The NCOM with two layers of nested grids is used to generate realistic 3-D hydrostatic simulations of the Chesapeake Bay outflow plume. The plume is generated by rivers flowing into the Chesapeake bay. The flow through the mouth of the bay is strongly forced by the tides. The winds strongly modulate the flow especially on the continental shelf outside the mouth of the bay. Northerly winds push the plume south and compress it against the coast. Southerly winds widen the plume and the upwelling induced on the onshore side of the plume forces the plume off shore.

In future work we will focus on frontal following coordinate systems and improved horizontal boundary conditions for the small-scale 3-D nonhydrostatic simulations. This will allow us to investigate the origin, evolution and impact of transverse and 3-D structures and instabilities of the plume dynamics.

For the large scale hydrostatic simulations we are working on more realistic forcing including outputs from operational atmospheric models such as the COAMPS and flow rates from river gauges. We will examine the impact of topography at different scales and the interaction between the river, tidal and wind forcing.

Acknowledgments. This work was done at the Naval Research Laboratory at Stennis Space Center, MS. The work was funded by the Office of Naval Research through the Physics of Coastal Remote Sensing Accelerated Research Initiative which is managed by Richard Mied.

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